Optimizing the Performance of RF Cavities: Theoretical Analysis and Annealing Experiments on the Electrical Conductivity of Oxygen-Free Copper

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Abstract

We systematically investigated the effects of annealing on the electrical conductivity of oxygen-free copper for particle accelerator applications. As part of the CSNS upgrade project, we measured the conductivity of copper specimens treated at various annealing temperatures and conducted metallographic examinations to analyze changes in grain microstructure. Our results demonstrate that suitable annealing temperatures significantly enhance the electrical conductivity of oxygen-free copper and optimize its grain structure. These findings offer novel perspectives on copper cavity fabrication technology, particularly in optimizing crystalline structure through controlled recrystallization processes, which can advance the performance of particle accelerators.

Keywords: Annealing; Oxygen-Free Copper; Cavitiy; Conductivity

1. Introduction

The China Spallation Neutron Source (CSNS), a major scientific facility in China, generates high-flux neutron beams by bombarding a tungsten target with 1.6 GeV proton beams. These beams support diverse research areas, including energy materials and nuclear engineering [1]. To address evolving experimental requirements, the CSNS II upgrade will integrate two 648 MHz PIMS cavities at the linear accelerator's end. These cavities are designed as the debuncher to stabilize the beam's longitudinal distribution, thereby improving neutron beam quality for advanced

applications [2].

High-frequency cavities serve as essential elements in particle accelerator systems. Their primary role involves accelerating particle beams via electromagnetic fields while shaping the beam profile through precise control of distribution and energy dispersion [3]. The efficiency of these cavities depends critically on the electrical conductivity of their constituent materials. For instance, materials with superior conductivity not only boost energy storage capacity but also minimize resistive losses, ultimately elevating the accelerator's operational efficacy.

Oxygen-free copper (OFC), prized for its exceptional conductivity and ease of machining, has emerged as the material of choice for fabricating copper cavities [4]. A key challenge lies in the sensitivity of copper's conductivity to microstructural factors, such as grain evolution and processing-induced defects. Through systematic annealing experiments, we propose to identify optimal thermal treatment protocols. Controlled heating and cooling during annealing enable targeted modification of grain morphology and defect density, offering a viable pathway to conductivity enhancement. The research outcomes will directly support the performance enhancement of high-frequency copper cavities in the CSNS phase II upgrade project, providing a solid theoretical and technical foundation for CSNS to meet future research challenges with better efficiency and stronger performance.

2. Theoretical Background

2.1 Basic Principles and Influencing Factors of Copper Conductivity

Copper, as a typical transition metal, exhibits a significant characteristic: the absence of a distinct energy gap between its valence band and conduction band, with the two even partially overlapping in certain regions. This electronic structure feature implies that in copper, the conduction band is partially filled, allowing electrons to move freely within the conduction band without the need for additional energy transitions. This free mobility of electrons is one of the key factors contributing to copper's excellent electrical conductivity [5].

Copper atoms are arranged in a face-centered cubic (FCC) lattice structure in the solid state. Due to the atoms' close packing and high symmetry, a high degree of freedom is provided for the electrons.

Electron transport in copper is governed by multiple scattering mechanisms. These include interactions with phonons (quantized lattice vibrations), crystal defects (e.g., vacancies, dislocations), impurity atoms, and grain boundaries. Notably, phonon activity escalates at elevated temperatures, intensifying lattice vibrations and electron-phonon scattering frequency—a key factor in the temperature-dependent resistivity increase of metals. Concurrently, lattice imperfections such as point defects disrupt electron flow by acting as scattering centers, thereby degrading overall conductivity [6].

A critical metric for electron mobility is the mean free path l, defined as $l = vF * \tau$, where vF denotes the Fermi velocity (vF（Cu）=2.27*10^8(cm/s)) and τ

represents the scattering time. At cryogenic temperatures (4K), τ approaches 2x10^-9 seconds, whereas at 300 K, it plummets to 2x10^-14 seconds. Consequently, the room-temperature mean free path in copper reduces to approximately 30 nm. When material grain size nears this threshold, grain boundary scattering dominates, significantly impeding electron motion [5].

TU1-grade oxygen-free copper (OFC), a high-purity alloy (>99.97%Cu, <0.003% O), is engineered for ultra-low oxygen content. Oxygen-free copper not only possesses high electrical conductivity and good machinability but also exhibits excellent weldability due to its low oxygen content, effectively avoiding "hydrogen disease." Moreover, oxygen-free copper has a clean appearance, fewer defects, and superior surface quality. These attributes render TU1 OFC indispensable in precision vacuum components. In this study, TU1 OFC was selected for debuncher cavity construction to maximize operational reliability and performance [7].

2.2 Effects of Annealing on Copper Materials

Annealing, a heat treatment technique critical for microstructural optimization in metals, enhances material properties by modifying grain configurations. This process progresses through three sequential phases: recovery (stress relaxation), recrystallization (grain reformation), and grain growth (microstructural coarsening) [8].

During the recovery phase—the initial stage—point defects (e.g., vacancies) migrate and minor dislocation structures annihilate, effectively relieving internal stresses without altering the macroscopic grain architecture. As thermal exposure intensifies (via elevated temperatures or prolonged durations), recrystallization initiates: defect-depleted nuclei emerge within deformed grains, subsequently expanding to replace the original strained microstructure with low-defect crystalline domains. The recrystallization process reduces the material's dislocation density, thereby lowering hardness and increasing toughness. After recrystallization is complete, if the annealing temperature is still maintained, larger grains will continue to grow, while smaller grains gradually disappear, a process known as grain growth. The grain growth stage significantly impacts the material's final microstructure and properties [9-11].

According to existing literature, when copper materials undergo recrystallization treatment within the temperature range of 200°C to 500°C, their mechanical properties, such as strength and hardness, undergo significant changes. This indicates that adjustments to the material's microstructure can have important implications for its macroscopic properties. In light of this, this study conducted annealing experiments on a batch of copper samples to explore how different annealing temperatures affect the structural characteristics and electrical conductivity of the copper samples. Although the specific types of copper materials vary in the references, this experiment decided to use 450°C as the temperature point for the initial annealing experiment to analyze the impact of annealing treatment on the performance of copper samples [11-13].

2.3 Impact of Conductivity on Copper Cavity Performance

In RF cavities, conductivity directly influences the propagation and loss of electromagnetic waves. Higher conductivity can reduce the attenuation of electromagnetic waves on the material's surface because surface resistance decreases, energy loss is reduced, thereby enhancing the cavity's Q value (quality factor), enabling the cavity to store and transmit electromagnetic energy more effectively [14].

Surface resistivity $\mathrm{Rs} = \sqrt{\frac{\omega\mu}{2\sigma}}$, where ω is the angular frequency, μ is the material's magnetic permeability, and σ is the conductivity.

The quality factor of the cavity $Q = \frac{\omega\mu}{Rs} \frac{\int |H|^2 dV}{\int |H|^2 dS}$

3. Experimental and Methods

3.1 Material Preparation

The raw material selected for this experiment was oxygen-free copper TU1 produced by Chinalco Luoyang Copper in 2019. Using wire cutting technology, 12 uniformly sized slender rods (2mm x 2mm x 100mm) were cut from the copper material intended for cavity processing. Each sample underwent grinding, pickling, and polishing treatments before the experiment to ensure a clean and smooth surface.

3.2 Electrical Conductivity Measurement by the Kelvin Four-Wire Method

The four-wire measurement method is one of the standard methods for assessing the electrical conductivity of wire materials. This method involves introducing current at two ends of the sample and measuring the voltage difference between two internal points, thereby avoiding the influence of contact resistance on the measurement results. The experimental steps are simplified as follows:

1. Use a vernier caliper to mark a 70mm test length on the sample;
2. Connect the two ends of the sample to a high-precision DC constant current source (e.g., Keithley 2430 SourceMeter);
3. Measure the voltage difference at the marked 70mm length using a high-precision digital multimeter (e.g., Keithley 2002 MULTIMETER);
4. Apply currents of 1A, 2A, and 3A, and record the respective voltage readings.
5. Calculate the resistivity and conductivity based on the recorded data.

Resistance (R) is calculated using the formula (R = V/I), where (V) is the measured voltage difference, and (I) is the applied current. Then, conductivity (δ) can be calculated through (δ= 1/ρ=L/RA), where (L) is the measured length of the sample,

and (A) is the cross-sectional area.

Conductivity is expressed in terms of the International Annealed Copper Standard (%IACS), where 100%IACS corresponds to the conductivity of pure annealed copper at 20°C (68°F), approximately 58.0 MS/m. %IACS facilitates the comparison of electrical performance across different materials.

The resistivity (ρ) of copper as a function of temperature (T) can typically be approximated by the linear relationship: $\rho(T) = \rho_0[1 + \alpha(T - T_0)]$ where α is the temperature coefficient, $\alpha（Cu） = 0.00393K^{-1}$ in 20℃.

3.3 Vacuum Annealing Treatment

First, the copper samples, after conductivity measurement, were placed in vacuum annealing furnace， and the vacuum level was reduced to below 10^-4 mbar using a vacuum pump. Then, a temperature curve was set to increase the temperature at a rate of 5°C per minute to the predetermined target temperature. After maintaining the target temperature for 2 hours, the samples were allowed to cool naturally to room temperature in a vacuum environment, a process that typically takes 10 to 20 hours. Once the sample temperature returned to room temperature, the vacuum pump was turned off, the furnace pressure was allowed to return to atmospheric pressure, and the samples were removed. Before conducting the next round of conductivity measurements, the samples were stored in a vacuum-sealed container to maintain their state. It is particularly important to note that oxygen-free copper is highly susceptible to oxidation at high temperatures; therefore, it is essential to ensure that the sample temperature is below 30°C when removing it from the furnace to avoid oxidation.

In the initial vacuum annealing experiment, we selected 450°C as the target temperature and observed a significant improvement in the conductivity of the copper material. Subsequently, a series of different target temperatures (350°C, 400°C, 500°C, and 600°C) were chosen for vacuum annealing treatment of the samples. After each annealing treatment, a second conductivity measurement was performed on the samples.

3.4 Metallographic Analysis

Representative small samples were cut from each treated material, cold-mounted, and then subjected to multi-stage grinding and polishing to prepare smooth surfaces suitable for observation.

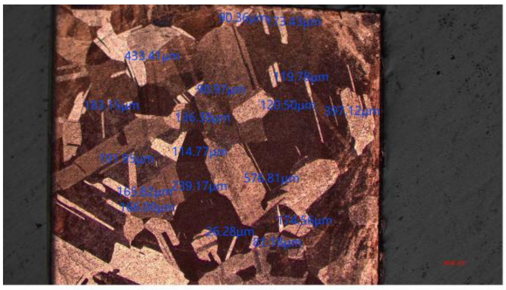
The polished samples, often mirror-like, were chemically etched using suitable etchants (e.g., ferric chloride solution, dilute nitric acid) to expose the microstructural features of the material.

The etched samples were placed under a metallographic microscope for observation and recording of the microstructure, such as grain size and shape, inclusions and defects, and grain boundary characteristics.

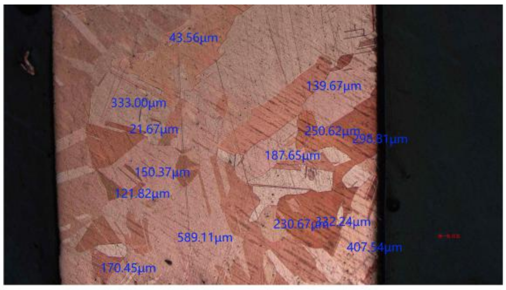
4. Results and Discussion

4.1 Metallographic Analysis

Metallographic analysis results showed significant changes in the grain structure of copper materials after annealing at different temperatures (350°C, 400°C, 500°C, and 600°C) (see Figure 1). In the unannealed copper material, a large number of smaller and closely packed needle-like grains were observed. However, as the annealing process progressed, the size of the grains gradually increased, the needle-like grains gradually decreased, and the grain boundaries began to become less distinct. These changes indicate that the annealing process significantly optimized the lattice defects, impurity distribution, and grain boundary structure. The enlargement of grains and blurring of boundaries indicate a reorganization of the material's internal microstructure.



a)



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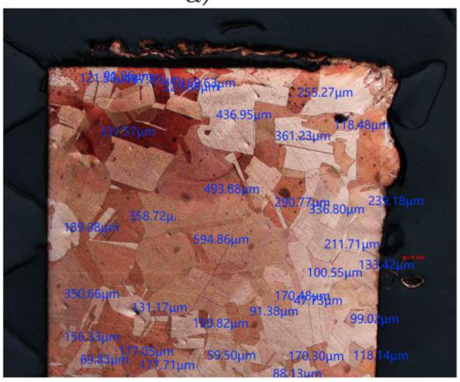

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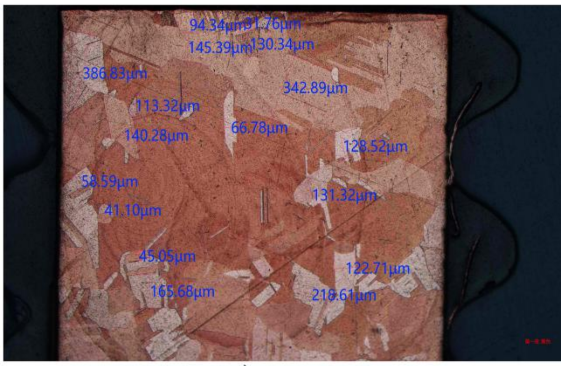

d)

e)

Figure 1: Metallographic Analysis of Copper Annealed at Different Temperatures. a) Unannealed;

b) Annealed at 350°C in a vacuum; c) Annealed at 400°C in a vacuum; d) Annealed at 500°C in a vacuum; e)Annealed at 600°C in a vacuum.

4.2 Changes in Conductivity Before and After Annealing

In this study, we measured the conductivity of copper materials treated with vacuum annealing at different temperatures. The experimental results showed an average increase in conductivity of 2.2% to 2.86% compared to the untreated copper materials (as shown in Figures 2 and 3). Notably, the samples annealed at 350°C for two hours in a vacuum exhibited the most significant increase in conductivity, reaching 2.86%.

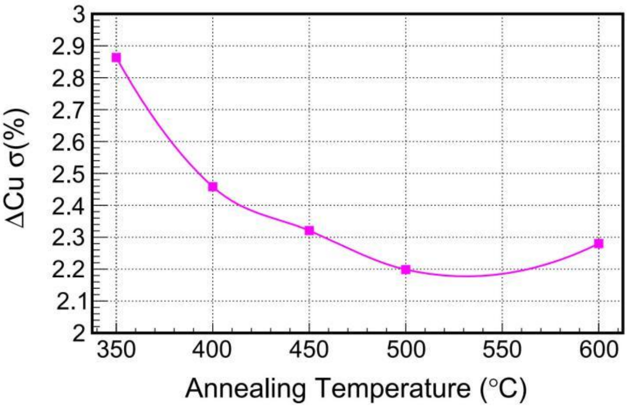

Figure 2: Change in Conductivity of Copper Samples at Different Annealing Temperatures.

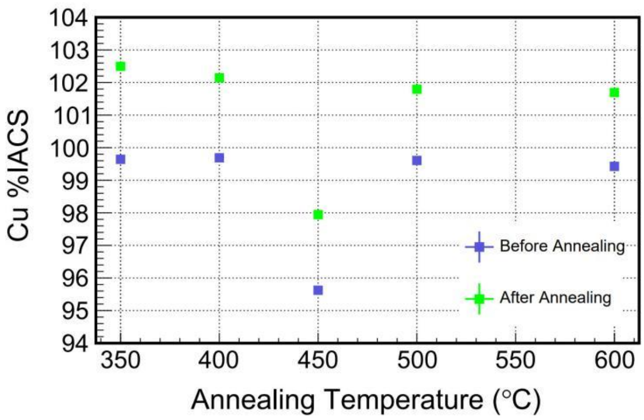

Figure 3: %IACS of Copper Before and After Annealing at Different Temperatures.

The experimental data revealed a nonlinear relationship between conductivity enhancement rate and annealing temperature (Figures 2). The measured conductivity enhancement rate peaked at 2.86% under 350°C annealing, followed by a gradual decline with increasing temperature, with only a minor recovery to 2.28% at 600°C. These results identify 350°C as the data-supported optimal annealing temperature.

Annealing temperature demonstrated a strong linear positive correlation with grain size (Pearson's $r = 0.95$, $p = 0.013$) (Figure 4). At 350°C, the average grain size measured 201.05 μm, significantly smaller than those observed in high-temperature

regimes (500–600°C, grain size ≥220 μm), confirming that low-temperature annealing avoids excessive grain growth.

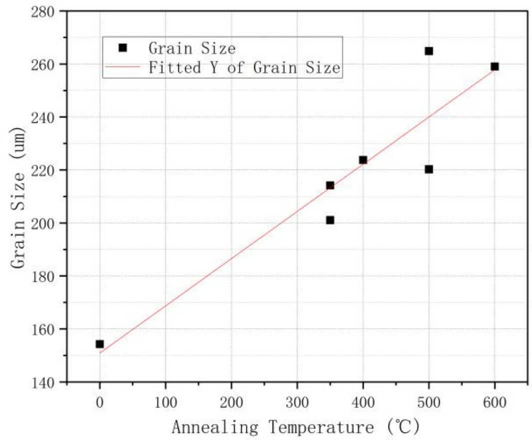

Figure 4: Grain Size of Copper After Annealing at Different Temperatures.

A moderate direct correlation ($r = 0.57$) was observed between grain size and conductivity (Figure 5), though statistically insignificant ($p = 0.32$). This suggests that conductivity optimization is not solely governed by grain growth, potentially involving temperature-activated mechanisms such as dislocation rearrangement or impurity redistribution.

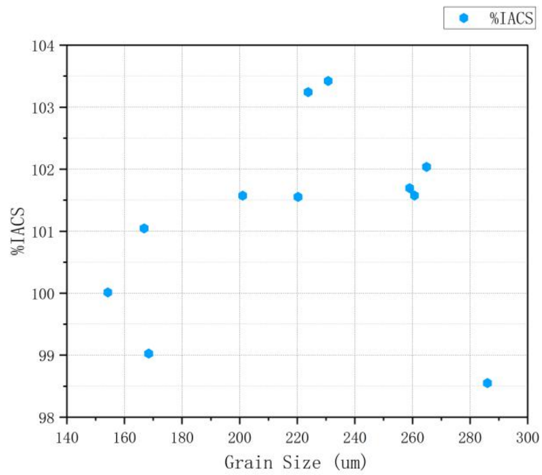

Figure 5: %IACS of Copper vs. Grain Size of Copper.

Figure 3 indicates that the conductivity of samples annealed at 450°C was lower. This is attributed to the first batch of samples being subjected to a brazing process in a furnace at 900°C along with the debuncher cavity prior to the experiment. At this temperature, the grains underwent excessive growth, and the overly enlarged grains led to the formation of new defects, thereby negatively affecting conductivity. Nevertheless, annealing at 450°C still resulted in a 2.3% increase in conductivity, indicating that the material's defect areas underwent a recrystallization process.

After more refined vacuum annealing treatment, the conductivity of this batch of domestic copper could approach 103%IACS, a considerably high level of conductivity, indicating significant improvements in internal defects, dislocations, etc.

4.3 Changes in Cavity Performance

The relationship between the quality factor (Q) of RF cavities in particle accelerators and conductivity (σ) can be approximated as: $Q \propto \sigma$. Therefore, a relative increase in conductivity ($\Delta\sigma/\sigma$) will lead to a relative increase in Q value ($\Delta Q/Q$). Given a conductivity increase of 2.86%, the theoretical increase in Q value is 1.4%. Good conductivity can improve the Q value of the cavity, reduce power loss, and enhance the efficiency of the cavity.

Vacuum annealing offers a twofold benefit: enhancing electrical conductivity and optimizing crystalline microstructure. By mitigating lattice defects, this process significantly improves the conductivity performance of copper. Similar to the low-temperature baking techniques employed in superconducting cavity optimization, vacuum annealing demonstrates broad applicability in microstructure control—extending beyond copper to superconducting metals such as niobium. Precise adjustment of annealing parameters (temperature, dwell time, cooling rate) enables tailored modulation of grain morphology, thereby governing macroscopic properties including electrical conductivity and mechanical strength.

During the manufacturing process of RF cavities, which includes welding, cutting, polishing, and other critical steps, these processing procedures significantly affect the microstructure of the cavity's inner surface. As clearly shown in Figure 6, compared to the unprocessed parts, the areas of the cavity that underwent mechanical processing and welding exhibit a more fragmented grain structure. This microstructural difference directly relates to the cavity's conductivity and overall performance.

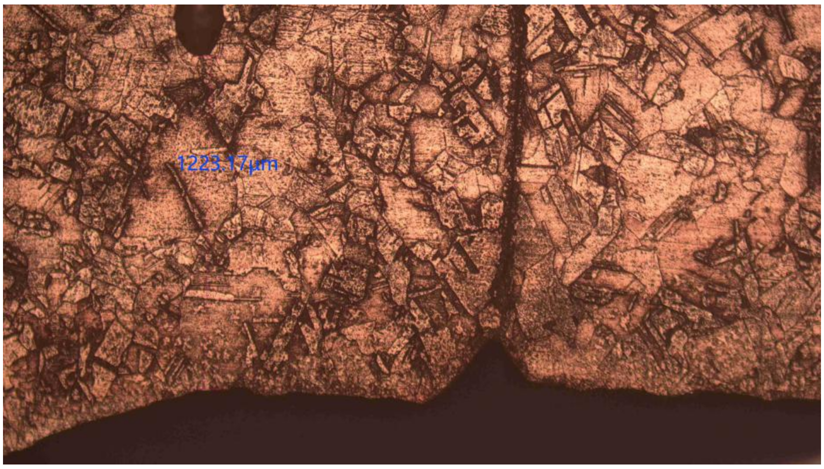

Figure 6: Grain appearance of machined surface under microscope.

To overcome the potential adverse effects introduced during the processing,

vacuum annealing treatment can be considered a step for RF cavities. Vacuum annealing can promote grain recrystallization and growth, thereby reducing the number of grain boundaries and improving grain structure. In this way, the conductivity of the cavity can be effectively increased, electron scattering reduced, thereby optimizing the overall performance of the RF cavity.

5. Conclusions

This study focuses on the beam dump components of the upgrade plan for the China Spallation Neutron Source (CSNS) and delves into the effects of annealing on the conductivity of copper materials and the performance of RF cavities through vacuum annealing treatment. Through a series of experiments and analyses, we have arrived at the following main conclusions:

The experimental results indicate that precisely controlled vacuum annealing treatment can significantly enhance the conductivity of copper materials. After two hours of vacuum annealing at 350°C, the conductivity of the samples increased by an average of 2.2% to 2.86%, with specific conditions yielding improvements up to 2.86%, approaching 103%IACS. This outcome validates the effectiveness of vacuum annealing treatment in enhancing material conductivity.

Metallographic analyses demonstrate that annealing mitigates lattice defects—notably vacancies and dislocations—while optimizing grain morphology. Such microstructural improvements suppress electron scattering, directly enhancing conductive performance.

Crucially, vacuum annealing's defect-reduction mechanism exhibits broad applicability. Beyond copper, this method can be extended to superconducting metals such as niobium, offering a universal strategy for fabricating high-performance RF cavities. This might explain from a microscopic perspective the necessity of low-temperature baking for the performance of superconducting cavities. Thermal treatment enhances RF cavity performance not only by improving electrical conductivity but also by optimizing surface defects and microstructure, significantly reducing field emission and quench probability to extend operational lifetime. This comprehensive optimization demonstrates the potential for thermal treatment to play an expanded role in advancing RF cavity performance.

In summary, vacuum annealing treatment is an effective means not only to significantly improve the conductivity of copper materials but also to optimize their microstructure, thereby enhancing the overall performance of RF cavities. These findings have certain implications for the selection of materials and subsequent processing for precision devices such as particle accelerators.

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